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Influence of Dimethyl Ether Combustion in the Compression-Ignition Engine on the Peak and Effective Measures of the Vibroacoustic Process and Toxic Compounds Emission

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ABSTRACT

The scientific paper conducted empirical studies related to the effectiveness of the use of dimethyl ether as an additive to diesel fuel and its impact on the efficiency of the mixture creation and combustion process. The measure of the above quality was the observation and parametric assessment of the then generated vibroacoustic processes, the relations of which were assessed using the peak and effective value of vibration accelerations, and also assessment of toxic exhaust gas components. The transformation of the main process into its vibroacoustic and emission representations allowed for the construction of mathematical relations between them, expressed in a specific engine operating space, and a vector of tribological parameters, expressing specific friction changes occurring in the critical kinematic pairs of the combustion and mixture formation area. The tests were carried out on a single-cylinder research engine with direct fuel injection, in stationary conditions with a time-invariant control vector. As part of the procedures, a constant and optimal value of thermodynamic parameters defining the thermal state of the engine was maintained, minimizing external forces and disturbances that could affect the active value of the measurement signal. The research results are empirical vibroacoustic and emission characteristics for various signal domains and their parameterization supplemented with a detailed analysis of the results, developed vibroacoustic and emission mathematical models depending on the operating parameters, type of fuel and combustible mixture formation variables, supplemented with an assessment of their degree of mapping to the dynamic source process. The dimethyl ether application resulted in a emission reduction by the coefficient: 24.3–57.8 (hydrocarbons), 1.03–1.24 (carbon monoxide), and an increase in nitrogen oxides in the range of 1.01–1.08. The use of dimethyl ether as a base fuel component has a positive effect on reducing the peak value of vibration accelerations in the range of 16–28%, and the root mean square in the range of 14–65%.

Keywords: alternative fuels, vibroacoustics, combustion efficiency, impulse and energy measures.

INTRODUCTION

The development of systems for managing the supply and conversion of energy in stationary and traction drive systems is aimed at meeting the increasingly higher requirements that arise and evaluate, which have their source in both the economic and social space of global, national and local markets. Multi-level and multidimensional assessment criteria, with different nature of expectations regarding the systems' drive sources, are additionally supplemented with restrictive expectations regarding minimizing the environmental harmfulness of the effects of energy generation and conversion processes in thermodynamic systems. Its basis is to reduce the emission of harmful and toxic exhaust gases [1, 2] as well as the level of noise amplitude, intensity and power, while maintaining the same operational properties of the facility (or increasing them). Meeting multiple, often contradictory requirements requires a multidisciplinary approach to the process of designing and operating the facility in real working conditions. The basis of the world's main directions of research on energy sources and drives of machines and vehicles is, among others, the search for alternative fuels [3–6], the processing of which would enable the fulfilment of both high operational and emission requirements, the potential of which would enable their further development in the face of future tightening of emission standards [7–9].

The currently observed development of electric drives (also using fuel cells) is accompanied by activities aimed at the composition of various forms of alternative fuels, either in whole or as a specific share in conventional fuel (using biocomponents) [10, 11]. Such fuel improvement processes must be accompanied by a process of physical and chemical verification of their properties [12–14] and empirical assessment of the impact on the overall engine efficiency, which is based on a quantitative assessment of the quality and efficiency of the formation and combustion [8, 15–19] of the fuel-air mixture (or the generation and conversion of energy into electricity and further in effective work) in the drive source and the stability of its parameters in relation to the operating and environmental conditions for a specific power receiver and external factors of its operation.

The verification of research hypotheses must take into account the empirical representation of the data matrix representing work parameters and indicators, as a result of the efficiency of creating and burning the composed fuel in the operational space of the research object [20, 21]. Therefore, the selected multidimensional operating space of the technical object was filled with diagnostic parameters informing about the above-mentioned effectiveness. The above assessment was supplemented with a signal measurement of the concentrations of the main components of harmful exhaust gases, thanks to which it was possible to more fully assess the physical-chemical efficiency of the mixture creation process and its kinetic combustion in a given working space. The information obtained here is the basis for a detailed analysis of partial sources of irregularities or effects of a specific composition of fuel components [22–24].

Diagnosing processes and the degree of fulfilment of main goals formulated during the design of technical facilities, carried out in real conditions of their operation, requires the use of methods of their assessment that reproduce as faithfully as possible the runs of dynamic processes and their effects in space and changes in diagnostic parameters. The search for the above unambiguous functional relationship is an indispensable help when monitoring the technical object during its operation, providing ready tools for ongoing analyses both on the correctness of these processes, sources of possible irregularities at the early stage of their generation, the impact of particular modifications (design, operational, changes in fuel composition). This paper is a response to such expectations regarding the assessment of the impact of dimethyl ether (DME) combustion in a single-cylinder research engine on selected diagnostic parameters of main and accompanying processes. The latter are a particularly important element of this scientific work, as an expression of the search for methods and quantitative measures mapping the quality of fuel composition and the effectiveness of its preparation and combustion into impulse and energy measures of vibroacoustic processes.

According to the authors' opinion, it is possible to clearly represent the composition quality and combustion of the conventional fuel with DME, with a specific share in the parameter matrices for the amplitude domain. Such analyses will allow to verify the suitability of DME for use in drive systems for stationary and traction applications from the perspective of changes in emission standards [25–27] and other requirements for these systems in the future (e.g. regarding operational and strength properties, including material properties) [28]. Another purpose of these activities is to show to what extent it is possible to apply appropriate measures of vibroacoustic processes [29, 30] and their effectiveness and sensitivity to changes of various nature (physical-chemical, structural, operational, regulatory) for this type of diagnostic procedures. Thanks to these studies, the above hypotheses were verified, presenting detailed research effects and appropriate analyses in relation to specific independent variables determining the operating characteristics of the facility and the thermodynamic parameters of the fuel supply system. In the context of these empirical studies, there is also a verification of the possibility of linking the emission value for a specific harmful exhaust gas component with an appropriate measure of the vibroacoustic process, the broader meaning of which is the information value about the level of this emission and the correctness of the combustion process in the engine of fuel with a given chemical composition and share of components. The main goal of the scientific paper was to assess the impact of dimethyl ether (DME) as an additive to conventional fuel in a compression-ignition engine on its performance indicators and the parameters of the generated vibroacoustic processes and emission of toxic compounds.

RESEARCH STAND

The properties of the fuel and its preparation conditions for combustion determined the specificity of creating and equipping the measurement station with specific design and measurement elements. As an organic gas from the ether group, colourless and moderately soluble in water, it can be obtained from the natural gas, the coal or the biomass. Dimethyl ether is usually produced by dehydration of the methanol or by the synthesis, allowing it to be produced from fuels or the biomass. During the oxidation of a dimethyl ether, it is not necessary to break the C–C bond, which favours its oxidation to carbon dioxide (CO_2). The higher energy density than a methanol is an additional advantage when used as the fuel or as an additive.

Due to its state of matter, an appropriate system was prepared and designed for testing, enabling its storage and transport to a high-pressure pump, which was made difficult by differences in the compressibility of both components and their different phases (use of a high-pressure pump with a specific design of the pumping section) – Figure 1.

The fuel pump was driven by an electric motor using an inverter [7]. The values of the parameters of the fuel supplied to the engine were carried out taking into account the possibility of excessive increase of its temperature, as a result of which the results were independent of the variability of the above thermodynamic parameter.

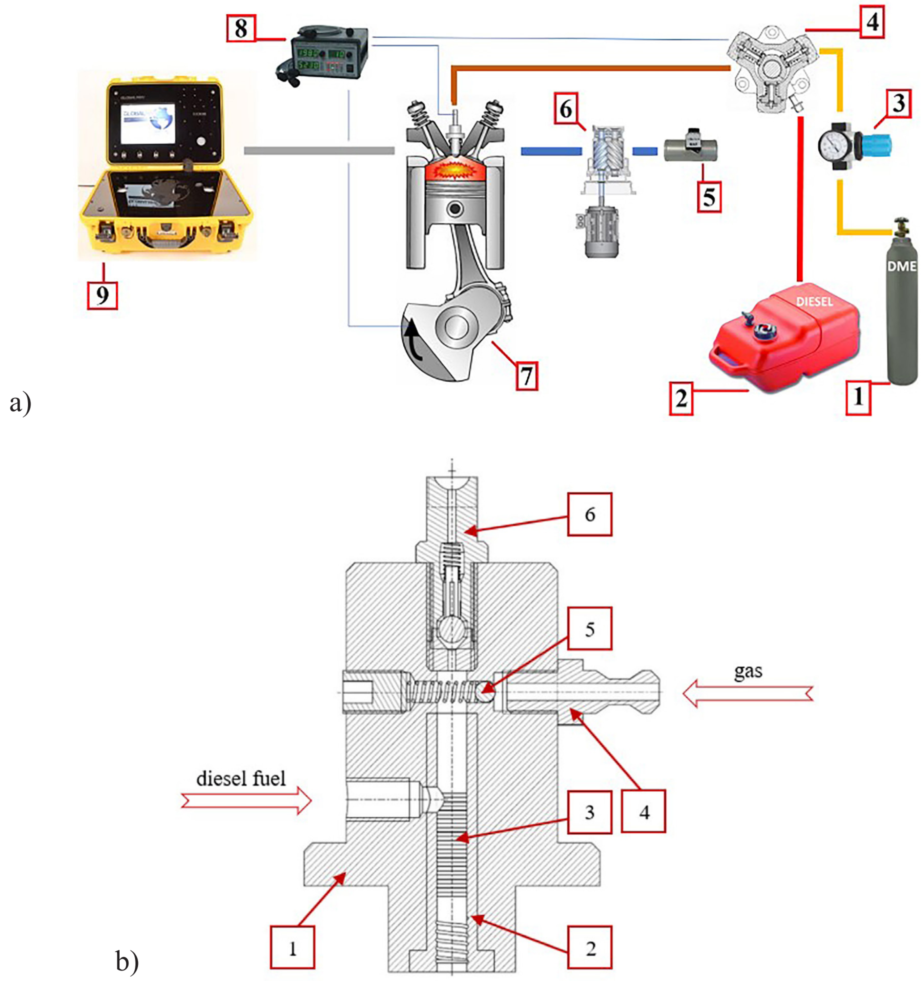

Figure 1. The scheme of a test stand (a) and fuel pump (b) for DME research: legend for (a): 1 – DME tank, 2 – Diesel tank, 3 – filtration block with pressure regulator, 4 – fuel pump/modified fuel pump, 5 – mass air flow meter, 6 – inlet air compressor, 7 – one-cylinder compression ignition engine, 8 – injection controller, 9 – exhaust gases analyzer; legend for (b): 1 – body of the delivery section, 2 – cylinder, 3 – section labyrinth seal, 4 – gas stub pipe, 5 – one-way gas valve, 6 – one-way outlet valve

Diesel fuel was supplied to the pump at a pressure of 0.5 MPa (thanks to the fuel pre-pump), while gaseous fuel was supplied directly to the system using conditioning (filtering and controlling the dissolved gas share using a pressure regulator). The quality of the combustion process using the above fuel-air mixture was also assessed by determining the emission of harmful exhaust gas components thanks to continuous measurement of the concentrations of components such as carbon monoxide (CO), hydrocarbons (HC), nitric oxide (NO), CO_2 and O_2 (using the Axion R/S system). Measurements were carried out in real time in the range and with the accuracy of: CO = 0–10% (±3%), HC = 0–4000 ppm (±3%), NO = 0–4000 ppm (±3%), CO_2 = 0–16% (±4%) i O_2 = 0–25% (±3%).

An additional factor influencing the constant value of the concentration of dissolved gas in diesel oil is the implementation of tests in stationary conditions, taking into account the constant values of engine speed and load (generated using an eddy current brake). The object of the research was a single-cylinder, four-stroke compression-ignition engine with direct fuel injection into the engine working space (the toroidal combustion chamber in a piston), with a liquid cooling system. The engine with dimensions: 950 mm (width), 1160 mm (length) and 1160 mm (height) and an engine displacement of 1845 cm^3 generates a compression ratio of 15.8 and a specific fuel consumption of 245 g/kWh. The maximum engine speed is 2500 rpm and the torque is 140 N·m. As part of the research, measurements of vibroacoustic quantities were also performed using the Pulse measuring system from Bruel&Kjær, type 3560C (Figure 2, Table 1) and a three-axis vibration acceleration transducer from Bruel&Kjær, type 4504A (Table 2). The synchronization of measurement signals with the specific position of the engine crankshaft was carried out using a Bruel&Kjær laser encoder type MM0360 (Table 3).

Alternative fuel specifications

As part of studies and empirical research, dimethyl ether was used as an alternative fuel burned in a research single-cylinder compression-ignition engine. The above fuel has physicochemical parameters similar to the conventional fuel used in compression ignition engines. The most important parameters of the presented fuel is given in the Table 4. Dimethyl ether was used in the tests as an additive to diesel fuel, which results from the properties of the above fuel. Low lubricity and viscosity increase the value of tangential forces during the cooperation of precision elements in the area of kinematic pairs. The effect of the above process is an increase in friction losses and wear of the surface layer of precision pairs in the injection system and the piston rings-cylinder liner system. Due to the good solubility of DME in diesel oil, it is appropriate to use it in the form of a solution, which will be released in the appropriate phase and burned with diesel oil. This solution was used by the authors of this scientific work, examining its impact on the combustion process and the generated

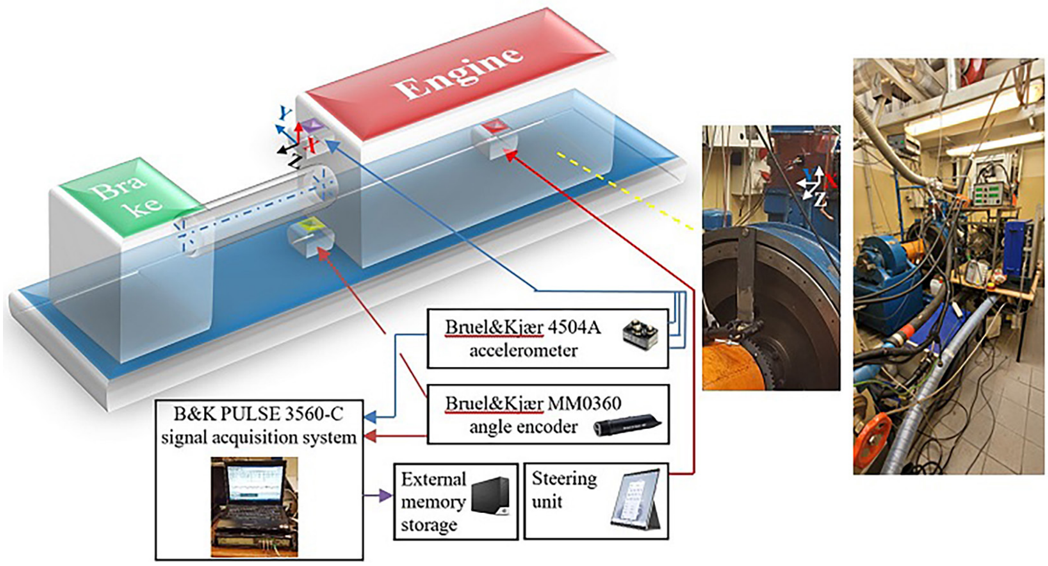

Figure 2. Type and arrangement of elements of the vibroacoustic measurement system for DME research

Table 1. Specification of the Bruel&Kjær Pulse 3560-C system [31]

Type of data	Value
Number of parallel input/output channels	5/1
Number of aux.channels	16
Type of an input channels	Direct, CCLD
Frequency range [Hz]	0–25600
Absolute amplitude precision (1 kHz, 1 V input)	±0.05 dB, typical ±0.01 dB
Absolute maximum input [Vpeak]	± 35
A/D conversion	2 × 24 bits
Voltage [V (DC)]	10−32
Nominal/max power consumption [W]	30/42
Dimensions: height/width/depth [m]	0.105/0.376/0.300

Table 2. Specification of the Bruel&Kjær 4504A transducer [32]

Type of data	Value
Frequency [Hz]	1–10000
Sensitivity [mV/g]	10
Working temperature [°C]	-50–125
Residual noise level in Spec. Freq. Range (RMS) [mg]	± 0.4
Maximum operational/shock level (peak) [g]	± 750/± 3000
Resonance frequency [kHz]	50
Triaxial/TEDS/Connector	Yes/No/10-32 UNF

Table 3. Specification of the B&K MM0360 angle encoder [33]

Type of data	Value
Velocity range [rpm]	0–300000
Operating range	1.5 (0.6) to > 70 cm (27”) and > 3° from centre line
Laser spot	< Φ5 mm at 70 cm distance
Maximum continuous input voltage [V]	–5 to +30
Laser class	3R, visible 660–690 nm, CW, P [optical] < 2 mW, complies with EN/IEC 60825–1: 2007
Operating temperature range [°C]	–10 to +50
Input type	CCLD (DeltaTron or ICP® inputs from 3 to 20 mA), U ≥ 20V

vibroacoustic processes. The image in the multidimensional space of vibroacoustic parameters was the basis for assessing changes in thermodynamic transformations in the engine and their effectiveness, including reflecting the quality of tribological processes and their energy exposure.

CONDITIONS OF EMPIRICAL STUDIES

The author’s empirical research was carried out in stationary conditions, for which the engine speed was selected at 900 rpm. For a given engine speed, the torque values changed in the range of 0–50 N·m, with an interval of 10 N·m (Table 5). The fuel injection pressure was kept constant at 40 MPa at each engine operating point. The fuel injection time into the engine was set with an accuracy of 0.1 ms, and the fuel injection angle up to 2.8125 degrees, which is related to dividing the engine operating cycle length of 720 degrees with the resolution value of 256 bit (limited by the encoder installation location: camshaft).

As part of the assessment of the reliability of the measurements, three measurement series were selected. The first of them concerned tests using a conventional injection system and a Bosch CP3 pump, while the next two series were carried out using a proprietary high-pressure injection pump allowing for gas dissolution. The external

Table 4. Dimethyl ether specification [34–36]

Parameter	Unit	Dimethyl ether	Diesel oil	δ = |DME/Diesel| [%]
Critical pressure	[MPa]	5.37	3.00	79
Lower calorific value	[MJ/kg]	27.6	42.5	35
Lower explosion limit	[% vol.]	3.2	0.6	433
Liquid density	[kg/m^3]	667	831	20
Upper explosion limit	[% vol.]	18	7	157
Kinematic viscosity of liquid	[cSt]	<0.1	3	> 97
Cetane index		57	40–50	14–42
Molar mass	[g/mol]	46.07	170	73%
Surface tension	[N/m]	0.012	0.027	55
Vapor pressure	[kPa]	530	<< 10	>> 5200
C/H ratio		0.337	0.516	34
Stoichiometric ratio of air and fuel		9	14.6	38
Chemical structure		CH_3–O–CH_3	–	–
Critical temperature	°C	126	434	71
Self-ignition temperature	°C	234	249	6
Boiling point at 1atm	°C	– 25	176–370	106–114
Oxygen content	[% mass]	34.8	0	–
Carbon content	[% mass]	52.2	86	39
Hydrogen content	[% mass]	13	14	7

controller was responsible for the appropriate regulation of a fuel pressure, carried out thanks to data obtained from the pressure sensor in the common rail tank. Thanks to it, it was possible to influence the electronic fuel dosing valve and the operation of the pressure regulator in the above tank. The value of the fuel injection pressure for each measurement series was set at 40 MPa in order to obtain the stability of the system and to clearly assess the impact of dissolving gases in the fuel and their impact on engine performance indicators, emissions of harmful components, impulse and energy parameters of vibroacoustic processes. Fuel injection time values were kept at a similar level both for conventional fuel and for DME with different supply pressures (Figure 3).

RESULTS AND THEIR ASSESMENT

The first stage of the analyses concerned the identification of the relationship between the engine load and the type of fuel used, as well as the specific pressure in the fuel supply system and the emission value of harmful and toxic exhaust gas components, such as HC, PM, CO and NO_x. The above parametric variability and its quantitative assessment made it possible not only to indicate the relationship between the quality of the process of creating the fuel-air mixture and its combustion and exhaust emission parameters, but also to verify the effects of using DME as a diesel fuel component. The observation of the increase in HC concentration in exhaust gases with

Table 5. Engine operating conditions defined in tests and corresponding emission measurement ranges

Engine speed n [rpm]	Engine torque M_o [N·m]	Injection pressure [MPa]	Number of measurement series	Emmision compound				
				CO [%]	HC [ppm]	NO [ppm]	CO_2 [%]	O_2 [%]
900	0	40	3	0–10	0–4000	0–4000	0–16	0–25
	10	40	3					
	20	40	3					
	30	40	3					
	40	40	3					
	50	40	3					

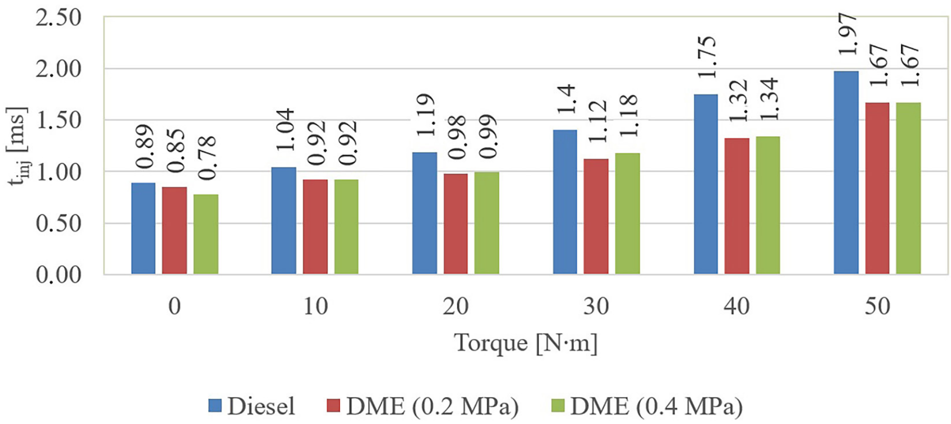

Figure 3. Differences in the fuel injection time values of diesel fuel and DME for different engine operating conditions (*n* = 950 rpm) and with different supply pressures

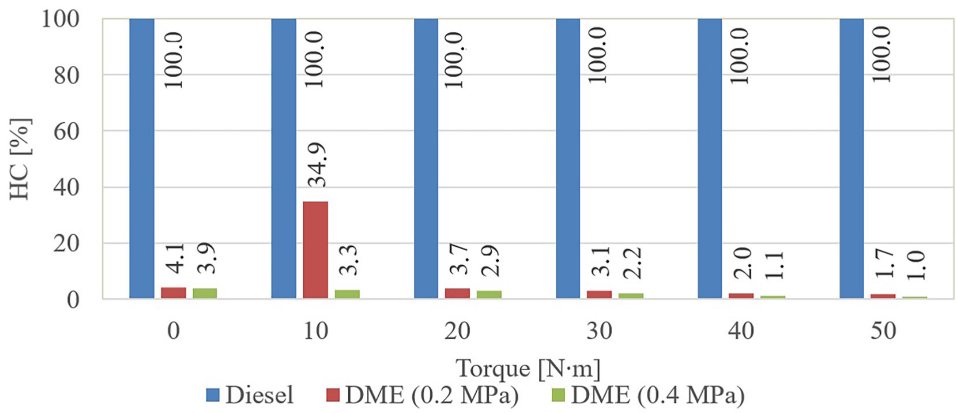

Figure 4. The influence of DME on the relative concentration of hydrocarbons (HC) in engine exhaust gases for different values of its torque and a supply pressure

the increase in torque confirms the existence of the above relationships and the validity of using this estimate as a diagnostic parameter in quantifying the quality of the combustion process in the engine (Figure 4). The use of dimethyl ether as fuel of the internal combustion engine of modern drive systems has a beneficial effect on reducing the HC concentration in exhaust gases. The emission reduction rate of the above exhaust gas component was within the range δ = 24.3–57.8 (δ means the quotient of the value obtained for pure diesel oil to the value for the diesel oil+DME mixture for a given torque value). Increasing the fuel supply pressure further reduces the above emission (more favourable physical and chemical structure of chains). The analysis of changes in PM concentration in exhaust gases confirms the increase in its value with engine power, which is closely related to the overall efficiency of the injection, mixing and combustion process of the mixture in the working space engine combustion chamber (Figure 5). The above changes confirm the impact of incomplete combustion in the engine under conditions of increasing load, accompanied by an increase in fuel dose per cycle, while the air flow rate remains unchanged for a given rotational speed. The use of DME as a fuel component is extremely beneficial because it significantly reduces the concentration of PM, which is consistent with the tendency of changes in modern emission standards towards lowering their maximum values (determined in the emission test). An increase in the fuel supply pressure causes a further reduction in this concentration, but to a lesser extent than for HC, which is influenced by the higher share of the insoluble solid particle fraction.

The increase in the engine load was accompanied by a gradual decrease in CO concentration in the exhaust gases (Figure 6). The increasing fuel dose in the engine's working cycle during load changes alters the physical-chemical structure of

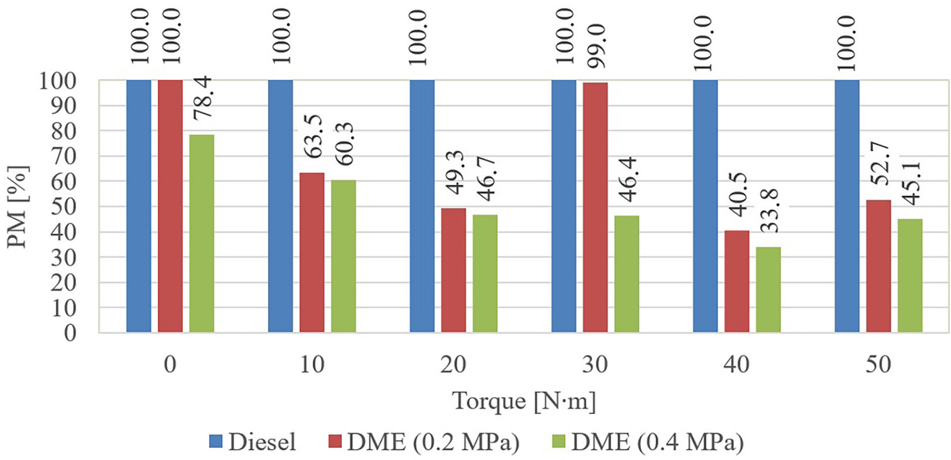

Figure 5. The influence of DME on the relative concentration of particulate matter (PM) in engine exhaust gases for different values of its torque and a supply pressure

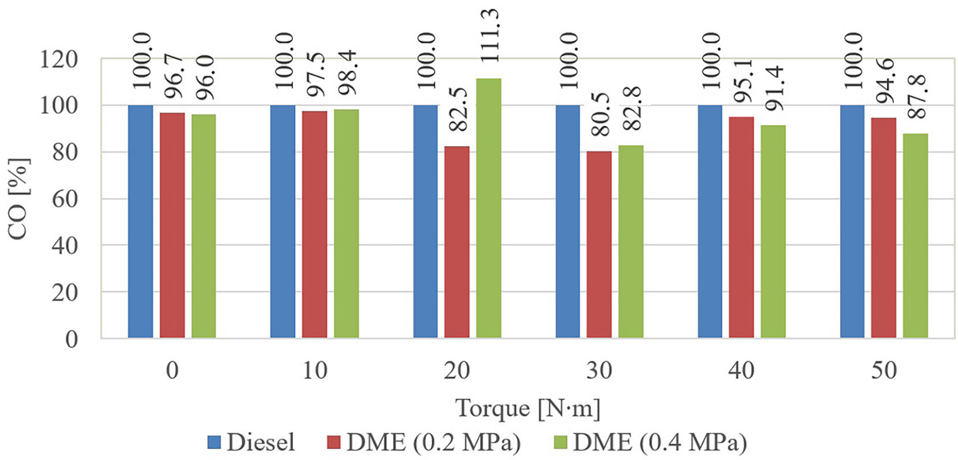

Figure 6. The influence of DME on the relative concentration of a carbon oxide (CO) in engine exhaust gases for different values of its torque and a supply pressure

the created mixture. The result is a specific relationship between the individual components of the combustion process and their combinations in the conditions of an incomplete thermodynamic process. HC and PM emissions increase as a result of that, at the expense of reducing CO emissions. The improvement in thermodynamic conditions observed in individual work cycles is an additional factor favouring this type of relationship in the emission balance, the measurable effect of which is an increase in temperature inside the combustion chamber, favouring the generation of nitrogen oxides (Figure 7). In the case of CO concentration, the application of dimethyl ether as a component of conventional fuel contributes to reducing the amount of this compound in exhaust gases in the range δ = 1.03–1.24. An increase in fuel supply pressure has a small impact on their reduction: δ = 1.007–1.07 (better for higher loads), however for lower loads it is not clear.

The increase in nitrogen oxides emissions, observed with an increase in a load (Figure 7), is caused by the average effective pressure rise in individual real thermodynamic cycles implemented for given stationary operating conditions of the tested system. The increase of the temperature values and kinetics of the combustion process (increase in a pressure over time) in these conditions, in accordance with the theory of generation and development of this chemical compound in these machines, favours more intensive formation of this component of exhaust gases.

The application of DME as a component of conventional fuel has a positive effect on the improvement of the thermodynamic cycle, which results in an increase in operational parameters

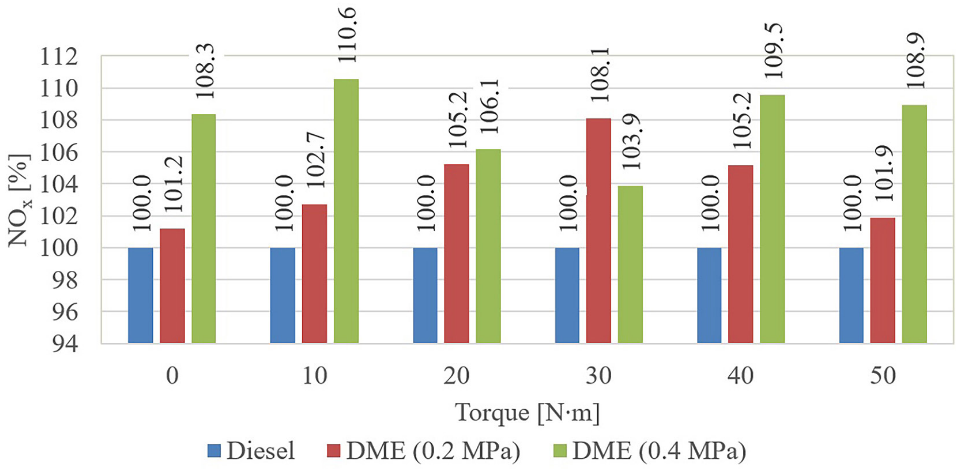

Figure 7. The influence of DME on the relative concentration of nitrogen oxides (NO_x) in engine exhaust gases for different values of its torque and a supply pressure

for the same fuel dose in particular engine cycles. When the fuel supply pressure for DME increases, the similar effects are achieved. The above processes determine a slight increase in nitrogen oxides emissions, which amounted to: δ = 1.01–1.08 (Figure 7). Also, an increase in the supply pressure caused a slight increase in the concentration of nitrogen oxides in these conditions in the range of δ = 1.008–1.07. Therefore, a negligible increase in NO_x is accompanied by relatively large beneficial changes in the reduction of other toxic exhaust gas compounds, thanks to the use of DME fuel in the combustion process and increasing the fuel supply pressure. The data presented above and their analysis make it possible to build clear functional relations for a specific exhaust gas component in relation to the variability of the engine power and a fuel type, which can be described in accordance with equations (1–12):

a) HC emission:

- for diesel fuel:

$$y = 0.0882x^2 - 0.2324x + 0.672\ (R^2 = 0.966) \quad (1)$$

- for diesel fuel + DME (fuel supple pressure: 0.2 MPa):

$$y = -0.0125x^4 + 0.1873x^3 - 0.9679x^2 + 1.9563x - 1.1385\ (R^2 = 0.881) \quad (2)$$

- for diesel fuel + DME (fuel supple pressure: 0.4 MPa):

$$y = 0.0001x^3 - 0.0012x^2 + 0.004x + 0.017\ (R^2 = 0.896) \quad (3)$$

b) PM emission:

- for diesel fuel:

$$y = 0.0882x^2 - 0.2324x + 0.672\ (R^2 = 0.966) \quad (4)$$

- for diesel fuel + DME (fuel supple pressure: 0.2 MPa):

$$y = 0.0409x^2 - 0.1302x + 0.549\ (R^2 = 0.800) \quad (5)$$

- for diesel fuel + DME (fuel supple pressure: 0.4 MPa):

$$y = 0.0555x^2 - 0.2662x + 0.641\ (R^2 = 0.985) \quad (6)$$

c) CO emission:

- for diesel fuel:

$$y = 3.2321x^2 - 37.282x + 183.3\ (R^2 = 0.993) \quad (7)$$

- for diesel fuel + DME (fuel supple pressure: 0.2 MPa):

$$y = 4.9821x^2 - 49.475x + 191.1\ (R^2 = 0.958) \quad (8)$$

- for diesel fuel + DME (fuel supple pressure: 0.4 MPa):

$$y = 2.3393x^2 - 32,632x + 175.9\ (R^2 = 0.956) \quad (9)$$

d) NO_x emission:

- for diesel fuel:

$$y = 89.286x + 165.67\ (R^2 = 0.993) \quad (10)$$

- for diesel fuel + DME (fuel supple pressure: 0.2 MPa):

$$y = 93.286x + 172.33\ (R^2 = 0.976) \quad (11)$$

- for diesel fuel + DME (fuel supple pressure: 0.4 MPa):

$$y = 96.886x + 176.4\ (R^2 = 0.997) \quad (12)$$

It is important to indicate whether there is a functional relationship between the kinetic combustion process and specific characteristics of the vibration process, as well as whether its variability resulting from the use of different fuel compositions can be reproduced. For this purpose, analyses were carried out for the time domain (Figure 8–9) and amplitude (Figure 10–12) domain, determining the above representation in the variability of dimensional measures of the vibration process: peak value (the impulse point measure) and root mean square (energy variability of the combustion process), presenting it for the X axis, representing the direction of movement of the piston in the cylinder (the greatest sensitivity to the combustion process). The above measurement axis was characterized by the highest dynamics of changes in the signal reflecting the combustion process, clearly maintaining the unidirectionality of the functional relations

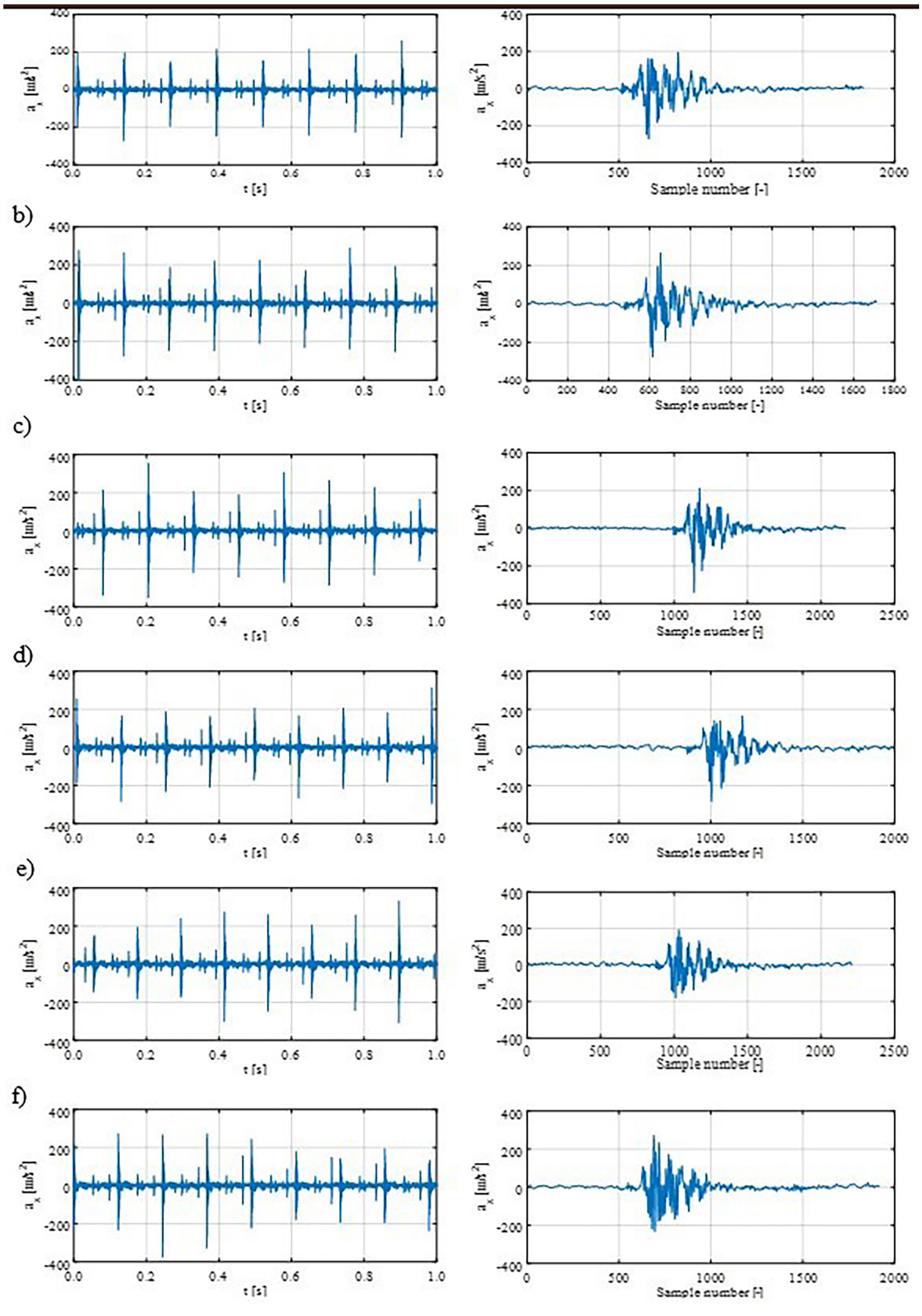

Figure 8. Time histories of vibration accelerations in the X direction (a_x) and fragments for the combustion process of a diesel fuel in the engine obtained at n = 950 rpm and Mo: (a) 0 N·m, (b) 10 N·m, (c) 20 N·m, (d) 30 N·m, (e) 40 N·m, (f) 50 N·m

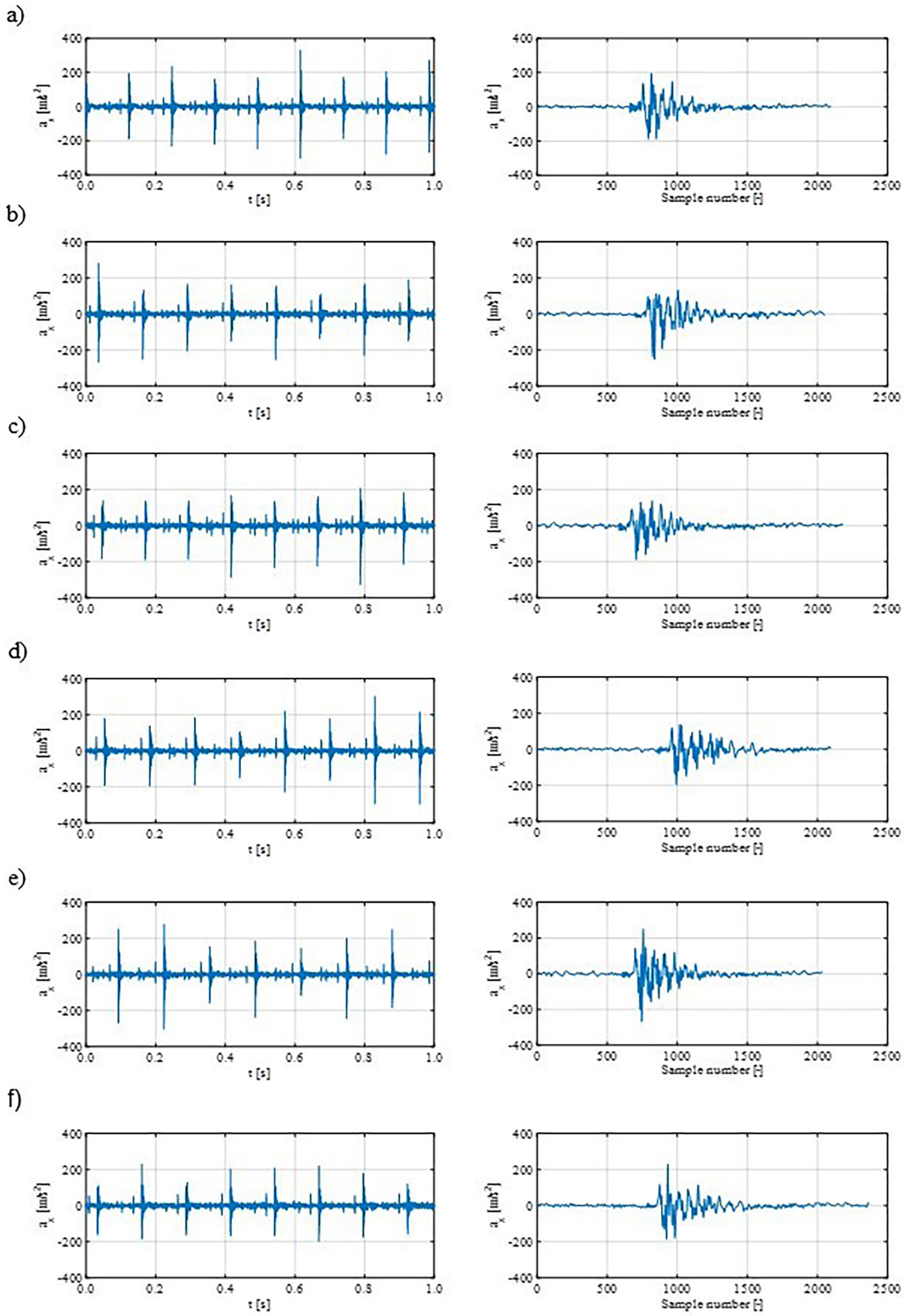

Figure 9. Time histories of vibration accelerations in the X direction (a_x) and fragments for the combustion process of a diesel+DME fuel in the engine obtained at n = 950 rpm and M_o:
(a) 0 N·m, (b) 10 N·m, (c) 20 N·m, (d) 30 N·m, (e) 40 N·m, (f) 50 N·m

between the dynamic process and its vibroacoustic representation in all conditions.

According to the time histories of vibration acceleration in the X direction (Figure 8) for diesel fuel combustion in stationary conditions represented by a constant value of engine rotational speed and load, one can see the unambiguity of the above thermodynamic process in its vibroacoustic representation, for each engine operating cycle. Moreover, the kinetics of the combustion process and the overall efficiency of converting the energy contained in a given fuel dose in each work cycle differ slightly, which is related to its real variability. The above relationship is reproduced precisely in the vibroacoustic characteristics equivalent to the source process,

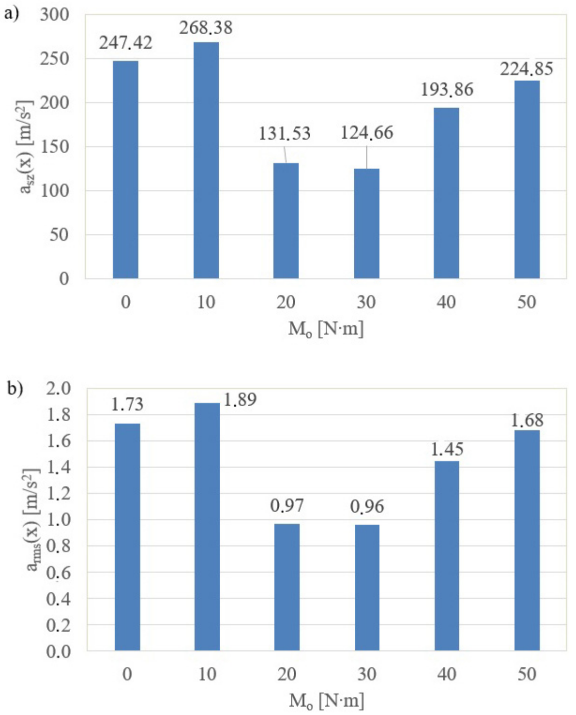

Figure 10. The influence of the combustion process of diesel fuel in the engine (fuel supply pressure: 0.2 MPa, n = 950 rpm) on the averaged point estimates of the vibroacoustic process for the X direction (obtained for the time domain): (a) peak value of vibration accelerations (a_p), b) root mean square value of vibration accelerations (a_{rms})

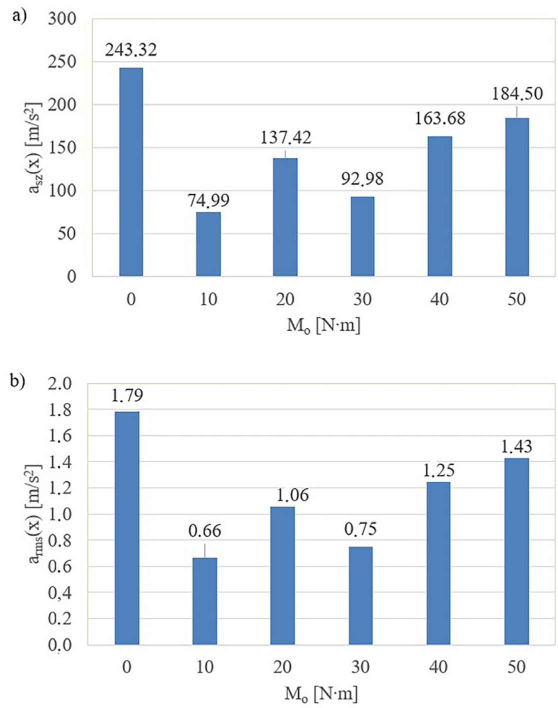

Figure 11. The influence of the combustion process of diesel fuel + DME in the engine (fuel supply pressure: 0.2 MPa, n = 950 rpm) on the averaged point estimates of the vibroacoustic process for the X direction (obtained for the time domain): (a) peak value of vibration accelerations (a_p), (b) root mean square value of vibration accelerations (a_{rms})

which makes further accurate evaluation of the signal and its quantification possible.

To assess the representativeness of sections from individual combustion cycles, an averaging process was also used (for a specific engine operating point). The analysis already at the time domain stage allows to indicate that both the amplitude and energy assessment can be a determinant of the search for differences in the kinetics of fuel combustion in the area of its nature, indication of the beginning and end of the process, the amount of converted energy, and overall thermodynamic efficiency. Already at this stage, an increase in the amplitude of vibration accelerations along with the increase in torque is noticeable. The increase in torque is also accompanied by an increase in the amount of energy obtained in the source process, mapped in its vibroacoustic representation, which can be seen for individual representations of the combustion process (Figure 8, right waveforms). It should be noted that the nature of the runs in terms of the characteristics of the combustion process does not change, which makes it possible to identify it in various system operating conditions (important in diagnostics of the object in real time, in the early detection of the first symptoms of process or design irregularities).

In the case of using DME as a component of diesel fuel (Figure 9), the relationship between the mixture creation and a combustion process and its vibroacoustic representation is also clear and strictly defined by the amplitude and energy variabilities. The increase in torque is accompanied by an increase in the amplitude and value of energy converted in the source process. Each cycle is distinguishable and its beginning and end are also discernible. The nature of the thermodynamic process, identified by its graphic form, does not change in various engine operating conditions, which means it can be identified for various process and design variables. However, the application of DME fuel has a positive effect on reducing both the peak value and the root mean square of vibration accelerations, which is visible for its individual time representations (Figure 9, right waveforms). The processes are more calm than in the case of using only diesel oil, and the

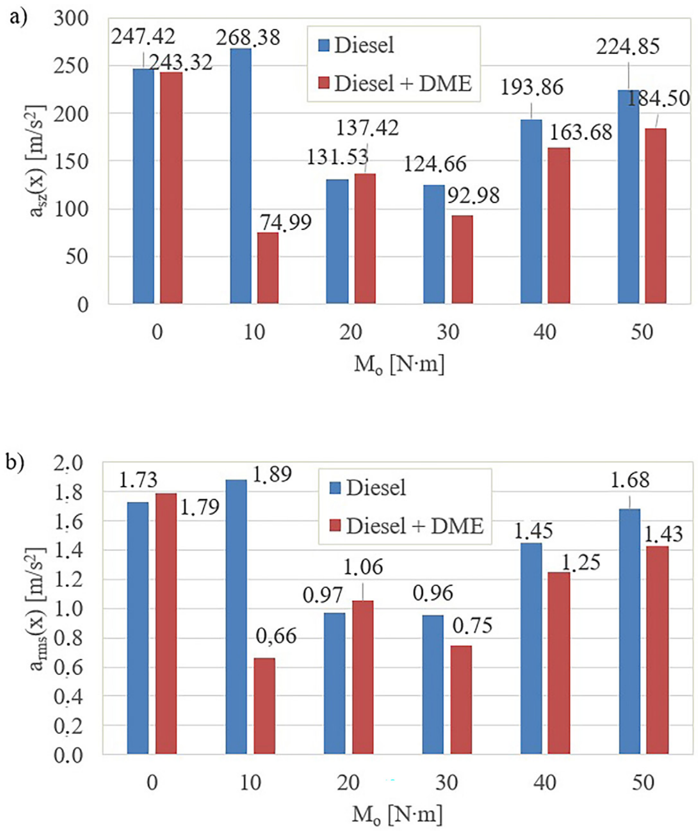

Figure 12. Comparison of the influence of the fuel type on the combustion run in the engine (fuel supple pressure: 0.2 MPa), mapped in the values of vibration acceleration in the X direction (obtained in the time domain) mapped for the averaged: (a) peak value (a_p), (b) root mean square value (a_{rms}), for different engine torques

amplitude values in individual work cycles differ to a lesser extent.

In order to clearly identify differences in amplitude and energy, an analysis was used in the amplitude domain, based on the assessment of the peak value and root mean square of vibration accelerations in the X direction for: changes in the engine torque, changes in the type of fuel used. Both measures were determined for a specific engine operating point in each combustion cycle. An averaging process was performed for the set of discrete values obtained in this way, obtaining a representative impulse and energy estimates (from all fragments representing the process of mixture formation and combustion in the engine). Thanks to this, the influence of torque on the average peak and root mean square value of vibration acceleration was obtained for both diesel fuel (Figure 10) and diesel oil + DME (Figure 11). According to Figure 10, the increase in torque raise the peak and RMS value of vibration accelerations, which proves the determinism of the relationship between the above estimates and the source process and its amplitude and energy variabilities. This increase is clear in amplitude and direction spheres in the range of 20–50 N·m, and in the case of 0–10 N·m only in the directionality area. Large amplitude values for this range may be the result of greater dynamic instability of the single-cylinder engine at no load, which results in greater differences in the measurement values for each engine operating cycle.

The use of dimethyl ether with a specific share in diesel fuel does not change the direction of torque influence on the obtained measures of the vibroacoustic process (Figure 11), which is beneficial in the context of the unambiguity of the relationship between the source process and its vibroacoustic counterpart. The increase in the peak value and RMS along with the increase in the amount of energy supplied and processed in the process of kinetic combustion of the mixture determines the quality of its run and the reliability of the diagnostic parameter and the validity of analyses for selected areas of the kinematic transformation of the data set for the signal vector. In this case, there is also an increase in the area of determinism of the process quantification in the field of low loads, where only for the lack of engine load the impact of dynamic thermodynamic non-stationarity on the amplitude form of the measures (its higher value) was noted, and not as previously for 0 N·m and 10 N·m. However, while the changes of both measures for pure diesel fuel was non-linear, the form of the equation describing changes in the peak value and root mean square for the composition: diesel fuel+DME approximates its linear representation. In order to assess the impact of the DME application on the amplitude and energy quality of the mixture creation and combustion process in various engine operating conditions, a comparison was made of the averaged values of vibration acceleration estimates (obtained from the fragments corresponding to the combustion processes for each of the engine operating cycles) for this type of fuel composition with its base equivalent (diesel fuel), as presented in Figure 12. The use of DME as a base fuel component has a positive effect on reducing the peak value of vibration accelerations in the range of 16–28%, and the root mean square in the range of 14–65%.

Determining the functional relationship between the point estimates and the engine load value for combustion of fuel with a specific chemical composition becomes important. In the case of both tested fuels, these relationships are described by the following equations:

- for the RMS value of the vibration acceleration and diesel fuel:

$$y = 0.0607x^2 - 0.042x + 0.9148 \quad (R^2 = 0.925) \tag{13}$$

- for the RMS value of the vibration acceleration and diesel fuel + DME:

$$y = 0.1222x^2 - 0.4492x + 1.3273 \quad (R^2 = 0.753) \tag{14}$$

- for the peak value of the vibration acceleration and diesel fuel:

$$y = 9.4642x^2 - 12.405x + 128.75 \quad (R^2 = 0.908) \tag{15}$$

- the peak value of the vibration acceleration and diesel fuel + DME:

$$y = 16.315x^2 - 60.381x + 173.24 \quad (R^2 = 0.709) \tag{16}$$

where: x – value of the engine torque.

The relationships obtained in this way between the combustion process of the fuel with a specific chemical composition under conditions of variable load of the thermodynamic system and the appropriate measures of the vibration process in the time and amplitude domains enable an accurate assessment of the process variability and the diagnosis of the object using these parameters in real time. Thanks to this, it is also possible to improve the developed mathematical models by combining the vibroacoustic representations with the equivalent compound of exhaust emissions, obtained in the equations (1–12).

CONCLUSIONS

The article presents a parametric assessment of the impact of dimethyl ether as a component of diesel fuel on the thermodynamic efficiency of the combustion process in a high-speed system with a cyclic operating process. Empirical tests were carried out in stationary conditions, where the independent variable was the torque value while maintaining constant rotational speed (as an expression of the variability of the mixture formation conditions and a kinetic combustion run). The efficiency of combustion kinetics was realized under the above conditions by comparing the combustion of pure diesel fuel and a mixture of diesel fuel with an appropriate DME share for a specific fuel supply pressure.

In order to assess the efficiency of the process of creating and burning fuel with a specific chemical composition, a new method of mapping the primary process obtained in the amplitude-energy transformation obtained in the vibroacoustic process was used. Thanks to this, clear functional relations were obtained between the course of the primary process and its counterpart in the time histogram of vibration accelerations (analysis in the time domain) for various operating conditions of the tested technical object, which were expressed in the parametric quantification of the quality of their representation and the overall efficiency of the combustion process, carried out in the field of amplitudes (the peak value and root mean square measures). In this way, innovative waveforms, their single cyclic representations and averaged waveforms were obtained (indicating the geometric and parametric repeatability in individual work cycles), as well as point measures of the vibroacoustic process sensitive to amplitude and energy variability. Thanks to this, mathematical models of the relationship between vibroacoustic estimates and combustion process variables (torque, fuel type, fuel supply pressure) were developed, based on the empirical data. In addition, the benefits of using dimethyl ether as a fuel for the generated vibrations of the object were pointed out, also in the context of diagnosing the thermodynamic system in real conditions. The use of DME as a base fuel component has a positive effect on reducing the peak value of vibration accelerations in the range of 16–28%, and the root mean square in the range of 14–65%.

Taking into account the existence of a functional relationship between the efficiency of the process of creating and combustion of the combustible mixture and the amount of harmful exhaust gas components (also in the context of meeting emission standards, efficiency of the process of designing and operating the facility, identifying irregularities), this work included an analysis of the emission values of HC, PM, CO and NO_x [37] to indicate the nature of these relationships for the tested fuel compositions. The emission reduction rate of the HC emission when DME component is used was within the range δ = 24.3–57.8, CO in the range δ = 1.03–1.24 and PM in the range δ = 1.27–2.95. Thanks to this, specific characteristics of changes in the concentration of a specific component were obtained for the tested conditions, which resulted in the designing of accurate models mapping the combustion efficiency for changes: torque, fuel type and fuel supply pressure.

The developed mathematical models for mapping the mixture creation and combustion process for diesel oil and DME in the parameters and characteristics of the vibration process provide the basis for further analyses using other fields of processing and vibroacoustic parameters, in the context of even more accurate monitoring of the source process, e.g. in non-stationary conditions or for other fuel compositions, and their practical application possibilities. Additionally, proprietary emission models can constitute the basis for the construction of hybrid models using both studied accompanying processes (scientific and application value), and in the future also using artificial intelligence methods.

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